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DEHYDRATED FOODSTUFFS IN THE TROPICS

CONSIDERABLE advances in the study of nutrition have taken place during the period between the first and present phases of the world war. Much more is now known of the nutritional requirements of men and animals, of the composition of foodstuffs and of the effects of processing on their composition. Diets, however, lag far behind in the Colonial tropics, for in many there is still an insufficiency of even the basic foods. Knowledge both of what constitutes an adequate diet for tropical dwellers and how this may be supplied by local foodstuffs is still very sparse. Since they are available for only brief periods the necessity for fresh green vegetables is strongly felt in the dry tropics and many curious articles of diet are consumed in the attempts to procure nutrients found by long experience to be essential. In the wet tropics, where green foods are available during most of, if not all, the year round, dietary deficiencies resulting from an insufficiency of fresh foods are mainly due to lack of knowledge concerning their necessity for sustained health. They are due in part also to low wages and in some places to lack of small holdings and the concentration of the population in towns. From the point of view of food storage, the dry tropics provide the main problems. Any means whereby either the produce of a short growing season in the dry tropics may be conserved or by which fresh foodstuffs (or food of equivalent value) may be transported from places where they are abundant to the dry tropics should assist in solving the problem of malnutrition. The ancient method of food-conservation by sun-drying is known to result in the loss of many of the essential vitamins and other accessory food substances from meat, fish, fruits and vegetables. Its extension would not go far towards remedying the main deficiencies of tropical diets. More modern methods of conservation and transportation, such as those now being applied with considerable success to foods produced in temperate climates must be used.

Of the various available methods—canning, cold storage, quick-freezing with subsequent cold storage and dehydration—the last two permit of a final product containing on the whole a higher proportion of the original content of protective food constituents, particularly vitamins. Of

these two, the dehydration method requires less processing plant and nothing further is needed than a relatively moisture-proof package for subsequent storage of the products. Also, most of the bulk of the foodstuff is removed as water, giving a commodity economical of storage space. The concentrated nature of these foodstuffs is, as one would expect, an important feature of their use as supplies for armies at overseas stations. A prominent feature of the rations carried by the German blitzkrieg armies was the compact nature of the dehydrated foods (1) ; these, by increasing the time during which the armies could remain independent of their commissariat contributed to their success in the field.

At a recent meeting in London (2) of the newly formed Nutrition Society, held jointly with the Food Group of the Society of Chemical Industry, accounts were given of progress made in improving the nutritive quality and palatability of dried foods. Dr. Kidd stated, in an introductory address, that while fundamentally no new discoveries had been made, nevertheless by bringing together what was already known in other branches of the food industry and applying the results to dehydration, it could now be said, in general, that the nutritive quality and palatability of dried foods were equal to those preserved by the established processes of canning and refrigeration. The main principles to be observed were : the destruction of enzymes by a short heat treatment before drying ; the maintenance of a low water content in the dried product during storage and distribution ; the exclusion of oxygen or retardation of oxidative changes by the use of anti-oxidants and the avoidance of contamination with traces of metal ; the avoidance of temperatures during drying above a certain limit which can easily be determined for any product, but nevertheless the drying to be done as quickly as possible by using air-currents, heated rollers &c. ; the avoidance of drying temperatures at which bacteria will flourish ; and lastly, the selection of the best material as regards flavour, appearance and nutritive value and the use of scrupulous cleanliness during the manufacturing operations. Good dried foods could not be hoped for if drying were used as a means of disposing of fresh food which had deteriorated too far for distribution in the fresh condition.

Although full details of the modern dehydration processes have not yet been published it is evident that these methods for preserving foods have been applied with success to such varied produce as meat, eggs, milk, fish, fruits and vegetables. It is, therefore, of interest to visualize what potential use these methods may have in the tropical colonies. Three possible applications can be suggested. During the war, tropically grown vegetables and fruits could be dried for export as supplies to the Services to relieve somewhat the demands on agriculture in other parts of the Empire and, post-war, they could assist in the supplying of famine-stricken parts of the world. In those colonies with continuous or long rainy seasons vegetables and fruits could be dried and used to supply colonies with only very short wet seasons ; also crops grown in the brief wet seasons of the more arid colonies could be conserved for local use throughout the year.

With the possible exceptions of bananas and pineapples it is not easy to mention any specific truly tropical fruit or vegetable grown, as yet, on a sufficiently large scale to warrant the establishment of a dehydrating plant in any particular colony. There are however, many possibilities. For example, the despised guava has been shown in South Africa (3) to give a satisfactory dried product, very high in Vitamin C concentration, which should suitably supplement the citrus fruits and juices at present required by the Forces. Tomatoes also can be grown in many parts of the tropics and dried. Amongst other fruits ; avocados, mangoes, melongenes and sweet peppers may be of value while numerous vegetables could be made available if sufficiently intensive culture were attempted. If the demand for supplies becomes sufficiently great for Colonial sources to be called upon, a relatively small amount of investigation, given a suitable small-scale plant, would suffice to show the practicability or otherwise of utilising various forms of local produce. Providing shipping facilities for the transport of the prepared vegetables and fruits can be organised this seems a possible way of supporting the war effort for those colonies which so far, with no lack of desire have been unable to contribute much.

Whilst all too little knowledge is available on what constitutes an adequate diet in the tropics that of many colonial peoples is considered deficient in many of the constituents known to be necessary under temperate conditions. This is particularly so for leaf-vegetables and fruits. Vitamin deficiencies are widespread and the actual quantity of consumable food is insufficient in many parts especially during certain periods in the year. In the wet tropics such deficiencies could be remedied by less concentration on the production of export crops and more on crops suitable for local consumption. However, other measures must be sought in those territories where rain is scarce for the greater part of the year. Here lies a possible fruitful utilisation of a satisfactory and relatively inexpensive preservation method. While refrigeration remained the sole means of conserving food in a relatively fresh condition there was little possibility of storage in the more sparsely populated areas outside the larger towns of the Colonial Empire. The

(1) ' Foods that aided Blitzkrieg ' : *Food Indust.* (1941) Vol. XIII, No. 1, p. 43.

(2) ' Dried foods ' : *Nature* (1942), Vol. CL, No. 3799, pp. 223-224.

(3) Boyes, W. W. and de Villiers, D. J. R. (1942).— Vitamin C Content of Guavas. *Farming in South Africa*, May.

introduction of small dehydrating plants at strategic points would overcome this and assist in maintaining a diet more satisfactory both in quantity and in quality, particularly as regards protective foods, all the year round. The possibility at least merits consideration and investigation.

Tropical seas are well endowed with fish but on the whole, through lack of suitable ships and of enterprise, relatively little sea-fishing is done. Supplies of a highly important food in which the diet of most tropical dwellers is lamentably deficient could be increased if tropical fishing industries were developed. Where suitable cold storage with or without quick-freezing, could be made available it would probably take precedence over dehydration treatment as the final product is more attractive to the eye. But in regions far distant from the sea a perfected dehydration industry for tropical fish would mean the arrival of a hitherto unknown foodstuff. Similarly, the increased development of tropical stock-farming and the dehydration of the meat and milk produced would provide foods unknown to the native peoples of many colonies.

The establishment and operation of a dehydrated food industry within the tropical Colonial Empire must clearly be designed for the benefit of the people and cannot be founded on an economic basis. The peoples with the least to offer are those with the greatest needs. However, the removal of undernourishment would greatly stimulate their abilities and productive powers, to the ultimate enrichment and benefit of the Empire as a whole. In this connection a brief pertinent quotation from the Report of the Committee on Nutrition in the Colonial Empire (4) may be made :

> " We do not doubt that if it were possible (as unfortunately it is not) to remove at one stroke all traces of malnutrition in the Colonial Empire there would be an immense gain in physical health, in mental alertness, and in material welfare. Money spent in improved nutrition should be a sound investment, yielding its dividend in the increased welfare of the community as a whole ". H. R. B.

(4) Report of the Committee on Nutrition in the Colonial Empire (1939), First Report, Pt. I.

REVIEW

THE CARIBBEAN FORESTER

The quarterly journal *Caribbean Forester* was inaugurated in 1939 through the energy and initiative of the Forest Experiment Station, Puerto Rico. Its aim is to "serve as a medium of interchange of knowledge among those interested in forestry in the islands and countries in or near the Caribbean Sea ".

Tropical forestry, which comprises a wide range of natural sciences, together with various aspects of engineering, presents a multitude of problems. Throughout the Caribbean region there are many workers and several groups of workers engaged in solving these problems, and it is clearly to the advantage of all if the results of their investigations are passed on to fellow workers through the medium of a journal, so that they may act as a practical help and inspiration to them. The range of subjects to be covered, therefore, is extremely wide and the volumes of the journal issued to date contain articles which include botany, ecology, silviculture, forest policy, insect pests and many other subjects.

The journal is attractively mimeographed and illustrated. It is bound in a yellow cover decorated in front by a wood cut depicting a tropical scene, below which is the appropriate motto " It is my pride and joy to be the shepherd of my country's trees ". To all articles published in English is appended a summary in Spanish and *vice versa*.

The latest issue No. 4 of Volume 3 contains, amongst other contributions, two ecological articles, one on the forest types of Tropical America and the other on the forest associations of British Honduras ; an account of the forest policy of Trinidad and Tobago ; a description of a recently evolved method of planting with tar-paper pots on difficult sites in Puerto Rico ; and a seed storage study of maga, *Montezuma speciosissima* Sesse & Moc.

We commend this journal to all who are interested in agriculture, forestry and land usage in the tropics.

R. L. B.

ALTERNATE BEARING IN VALENCIA ORANGE

The tendency towards alternate bearing by Valencia oranges has been studied in California. The results seem to indicate a depressing effect of a large crop on the amount of fruit in the succeeding crop, which effect increases with the length of time the crop remains on the tree. The only comparable published work is that of West and Barnard* in Australia supporting the conclusions of the authors with the exception that they report the production of large fruit of inferior quality in the light crop years and small fruit in the heavy crop years, whereas no consistent relationship between amount of crop and fruit size was discovered in the California experiments. A more technical report of the work in California appeared in *Proc. Amer. Soc. Hort. Sci. for* 1940, 38 : 196-201.—(*Horticultural Abstracts*, XII, No. 1, 1942.)

*West, E. S. and Barnard, C.—The alternation of heavy and light crops in the Valencia orange. *J. Coun. Sci. Industr. Res. Aust.*, 1935, 8 : 93-100.

A NOTE ON *GOSSYPIUM BREVILANATUM* HOCH.

BY

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A strain of *Gossypium brevilanatum* Hochreutiner (1925) was established in 1939 at the Cotton Research Station, Trinidad, from seed kindly supplied by Prof. Aug. Chevalier of the Musée d'Histoire Naturelle, Paris. This interesting cotton relative is indigenous, but apparently rare, in Madagascar. After many unsuccessful attempts to obtain fresh seed, Prof. Chevalier kindly forwarded seed taken from herbarium specimens several years old. These germinated excellently, and a number of plants were obtained. In vegetative characters they resemble *G. kirkii* very much more closely than other species of *Gossypium*.

The following is a description of the more important characters of the species:

G. brevilanatum. Woody shrub. In Trinidad growing to about 2 m. tall, usually unbranched until near the top. Stem not very strong, sprawling if left unsupported. Probably a sprawling shrub in its native habitat. Stipules small, falcate and persistent. Fruiting branches short sympodia, usually with three or four joints, bearing brilliant orange yellow flowers. Bracteoles small (2 cm. or less). Flowers not widely expanding. Stigma lobes free, not dilated or capitate, not usually spreading. Capsules about twice as long as broad, usually 5-locular, surface irregularly pitted; hairs on the capsule sutures few and inconspicuous. Seeds 8 or 9 per loculus, covered with a single coat of fine light brown hairs up to 12 mm. long.

Chromosome counts were made in root tip material by R. M. Madoo. Root tips were fixed in "Craf" (Randolph 1935) and stained in Gentian Violet. A typical plate is reproduced in Fig. 1. The somatic chromosome number was found to be 2n=24 (checked on 17 plates). A pair of long chromosomes was a marked feature of every plate examined.

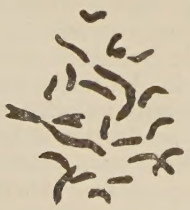

FIG. 1—*Gossypium brevilanatum*.

Somatic metaphase from root tip (× 5000)

As was expected, *G. brevilanatum* agrees with *G. kirkii* in chromosome number, and not with the true cottons. Plates of *G. brevilanatum* were compared with Skovsted's preparations of *G. kirkii*. Apart from the occurrence of one pair of long chromosomes in *G. brevilanatum* there was little difference in chromosome size between the two species.

G. kirkii and *G. brevilanatum* differ in a number of characters, the more important of which are tabulated below:—

Character.	*G. kirkii.*	*G. brevilanatum.*
Stipules	Large, oblique, clasping stem.	Small, falcate.
Bracteoles	Almost as long as the petals.	Very much shorter than the petals.
Stigmas	Free, spreading.	Free, erect.
Capsules		
Shape	About as broad as long.	Half as broad as long.
Suture hairs	Copious, almost filling the cavity.	Few and inconspicuous.
Seeds per loculus	2	8-9

G. brevilanatum grafts easily on *G. kirkii*, but attempts to graft *G. aridum*, *G. arboreum*, *G. hirsutum* and *G. barbadense* on *G. brevilanatum* stocks all failed.*

Attempts were made to obtain hybrids between *G. brevilanatum* and *G. kirkii*, and *G. brevilanatum* and cultivated New World cottons. 179 flowers of *G. kirkii* were pollinated by *G. brevilanatum*. The young bolls developed to some extent, but all fell off within about two weeks of pollination. At the same time attempts were made to cross two forms of *G. kirkii* that only differ slightly from each other. 46 flowers were pollinated, and all were shed within about two weeks. Since inter-crosses within *G. kirkii* failed, no great significance can be attached to the failure of crosses between *G. kirkii* and other species of *Gossypium*.

Eleven flowers of various types of *G. hirsutum* and seven of types of *G. barbadense* were also pollinated by *G. brevilanatum*. All were shed in three or four days.

References

Hochreutiner, B. P. G., 1925. *Candollea* **11**, fasc. 2, 20.
Randolph, L. F., 1935. *Stain Tech.* **10**, 95.

* It is of interest to note that the Hawaiian *Kokia rockii*, which is a relative of *Gossypium* with 12 pairs of chromosomes, will graft on to *G. kirkii*. A good union results, but there does not appear to be free translocation from scion to stock, as the root dies unless a branch of *G. kirkii* is left.

The Editor requests that any subscriber who fails to receive *Tropical Agriculture* regularly should communicate with him immediately in order that the matter may be rectified.

WITCHES' BROOM DISEASE INVESTIGATIONS

III. Notes on the Occurrence of Witches' Broom Disease of Cacao at River Estate, 1939-1942

BY

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From September 1939 to September 1942 detailed records were kept of the occurrence of witches' brooms on a plot of 76 trees at River Estate, Diego Martin. Much of the field recording was carried out by Messrs. S. H. Crowdy and R. K. McKee to whom the writer is indebted for their help. The trees were eight years old at the beginning of the experiment, 14 feet apart with Immortel shade, the latter poor and still inadequate. The trees represent the open pollinated seedling progeny of the selection I.C.S.1 and can be taken as representative of a good type of seedling cacao.

Table I

Brooms removed 1939 to 1942

	1939-40	1940-41	1941-42
Total brooms ...	3,901	12,321	15,612
Mean per tree ...	51	162	205
Fan and *Chupon brooms only	1,793	5,616	10,253
Mean per tree ...	23	74	135
Cushion brooms only	2,108	6,705	5,359
Mean per tree ...	28	88	70

* Chupon brooms are rare and represent less than 1 per cent. of the total.

The disease has rapidly become worse during the course of the investigation (Table I). This is illustrated best by the fan-brooms, of which under 2,000 were removed in 1939-40, about 6,000 in 1940-41, and over 10,000 in 1941-42. It is not likely that any great part of this increase was due to the growth of the trees, whose branches were already interlacing in 1939, or to increasing efficiency of the investigators in spotting brooms. The disease is becoming exceedingly severe on this property, as bad or worse than at most places in Trinidad, and there is no reason to believe that it has yet reached its maximum. There is, however, reason to believe that the maximum for certain trees in the plot has been reached as there is evidence to show that trees have been severely damaged and even thrown out of production by the intensity which the disease had reached by 1942. At the same time the severe dry seasons of 1941 and 1942 have had a marked effect on these trees and it is impossible to distinguish entirely the amount of damage caused by drought and that caused by witches' broom disease. The 1942-43 season is proving a very bad one for witches' broom disease at any rate at River Estate. The rains came early and have been heavy and prolonged ; rain has also continued with little intermission through the months of September and October when drier weather may be expected in most years. By October 1942 the incidence of the disease was already nearly double that of the previous year at the same time and as high as the previous year's maximum, which occurred in December-January. Also the rate of production of sporophores, on which the severity of the disease largely depends, had already become very high. It is reasonable to assume therefore that the position will become very much worse by January 1943.

Table II shows an analysis of the brooms removed from the plot during 1940-41 and 1941-42. The different types of broom A1, A2, A3, &c., are illustrated and described elsewhere (1). Briefly, 'A' brooms represent the terminal fan types, 'B' brooms the axillary fan types, 'C' the cushion brooms and 'D' the chupon brooms. The commonest types of fan-broom are the small lateral ones (B1 and B4) but larger fan-brooms (A2 and B2) occur in fair numbers. Of cushion-brooms the small ones without vegetative shoots (C3) are far the most abundant. Chupon brooms (D) are rare as chupons are normally removed as they appear. As brooms are removed from these trees every fortnight it is likely that some of them had not reached their full size when they were cut off, and an analysis of brooms removed at longer intervals shows a higher percentage of the larger types. The reduction of cushion-broom formation in 1941-42 is remarkable ; it is in no way a sign that the disease is diminishing as fan-brooms increased nearly 100 per cent. over the same period (Table II) ; but rather, since cushion-broom formation and flower production are strongly correlated, an indication that less flowers were produced during 1941-42. This may be attributed partly to the effects of the severe droughts of recent years on weak trees, but undoubtedly also to a large extent to the cumulative effect of severe attacks of witches' broom disease.

Table II

Types of Broom

Kind of Broom	1940-1941		1941-1942	
	Number	Per-centage	Number	Per-centage
*A1	633	5.1	1,267	8.1
A2 ...	1,067	8.7	1,454	9.3
A3 ...	363	2.9	442	2.8
A4/B1 ...	128	1.0	433	2.8
A4/B2 ...	47	0.4	136	0.9
A4/B4 ...	29	0.2	134	0.9
B1 ...	1,485	12.0	2,722	17.4
B2 ...	912	7.4	1,240	7.9
B3 ...	66	0.5	102	0.6
B4 ...	860	7.0	2,278	14.6
D1 ...	20	0.2	19	0.2
D2 ...	6	0.1	26	0.2
Total Fan and Chupon brooms	5,616	45.6	10,253	65.7
*C1 ...	24	0.2	19	0.1
C2 ...	1,326	10.8	1,016	6.5
C3 ...	5,295	43.0	4,276	27.4
C4 ...	60	0.5	48	0.3
Total Cushion brooms	6,705	54.4	5,359	34.3
Grand Total	12,321	100.0	15,612	100.0

* The illustrations of and the key to these broom types will be found in *Memoir* No. 7 *of the Dept. of Mycology and Bacteriology.*

Table III shows the total numbers of brooms per tree which have been removed during the three years of the experiment. Several points are noteworthy, firstly, the variation from tree to tree, the extreme range in 1941-42 being from 14 brooms recorded on tree 37 to 594 on tree 28. Secondly there are positive correlations (r=+0.77** and +0.73**) between the first and second, and second and third years results—it can be taken as an established fact that trees which produce many brooms one year are likely to do so again the next year, and that trees which produce only a few brooms one year are likely to behave similarly the next year. Thirdly, several trees (*e.g.* Nos. 27, 29, 35, 39, 48, 50 and 65) produced fewer brooms in 1941-42 than they did in 1940-41 although the total for the plot increased from 12321 to 15612, suggesting that these trees, which are amongst those which produced most brooms in 1940-41, have begun to show the effects of the disease. Certain trees, such as No. 1, which are exceptionally healthy, have produced large numbers of brooms without any noticeable loss of vigour.

Tables IV and V show fan-brooms and cushion-brooms analysed separately. The separation of brooms into two groups in this way makes an appreciable difference to the correlation co-efficients, fan-brooms per tree showing a higher positive correlation (r=+0.82** and r=+0.87**) than cushion-brooms (r=+0.76** and +0.58**) for the three years of the experiment.

The direct correlation between fan-brooms per tree and cushion brooms per tree (r=+0.34**) is low between the first two years and is lower still (r=+0.14) for the second and third years. This indicates that if there is any inherent relationship between the two it is masked by other factors, of which the most important appears to be the time for which the cushions remain active (and presumably open to infection) during the year. Some indication of this can be obtained from the intensity of flower production of the trees which was estimated every week for the second and third years of the investigation. The number of flowers produced during the year by any given tree is strongly correlated with the number of cushion-brooms produced during the year (1940-41 r= + 0.57,** 1941-42 r= +0.77**). It was therefore expected that if partial correlations were calculated and the effect of the intensity of flowering eliminated the correlations between fan-brooms and cushion-brooms per tree would be improved. However, no very strong correlations were found (1940-41 r=+0.51** 1941-42 r = +0.17).

It was also considered likely that since only young developing tissues can be infected by the disease the trees which 'flushed' most during the year should produce the largest number of fan-brooms. This was, however, found not to be the case (in 1940-41 r= + 0.05) between an estimation of the total flush per tree and the number of fan-brooms produced per tree. In 1941-42 a low positive correlation, (r=+0.22*) was obtained. Brooms, however, do tend to appear with the 'flush' or slightly before it, and there is a slight positive correlation (r=+0.31**) between the total flush figure for the plot for any week and the number of fan-brooms collected during the same week. This correlation was not appreciably improved by eliminating the dry season flushes which occurred at a time when no infection was possible.

The absence of substantial positive correlation between total flush and total fan-brooms per tree per year was quite unexpected and suggests that there are other important factors controlling the production of fan-brooms, and it is reasonable to assume that the most probable of these factors is a difference of susceptibility to the production of such brooms between the trees of the plot. But the strong positive correlation between the number of flowers produced and the number of cushion-brooms per tree per year suggests that

** Significant at 1 per cent. point
* Significant at 5 per cent. point
No star—not significant.

this resistance may not be an inherent protoplasmic one, but more likely some form of disease-avoidance on the part of certain trees. This is supported by the fact that fan-broom and cushion-broom production per tree do not appear to be closely correlated as would be expected if the resistance was an inherent protoplasmic one. Some purely morphological character such as longer or more abundant hairs on the buds, or more closely folding stipules covering the buds might account for it. It therefore does not follow that a tree which shows resistance to fan-brooms will show any comparable resistance to cushion-brooms or to pod infection. Conversely, a tree severely attacked by fan-brooms and cushion-brooms may produce pods which by reason of some character such as a very smooth or waxy skin, may tend to show resistance to the disease. These possibilities should be remembered when looking for resistance in Trinidad and in South American cacao. A tree markedly resistant as far as fan-brooms are concerned may be heavily attacked by cushion-brooms if it is free-flowering (*e.g.* tree No. 18), and we have as yet little data on the question of pod resistance.

There would however be great advantages in the use of trees which are resistant to fan-brooms and at the same time only flowered sparsely and thereby avoided serious cushion-broom infection. The number of brooms in the plantation

Table III

Total Brooms—September, 1939 to September, 1942

Tree No.	Total Brooms 1939-40	Total Brooms 1940-41	Total Brooms 1941-42	Tree No.	Total Brooms 1939-40	Total Brooms 1940-41	Total Brooms 1941-42
1 ...	55	285	397	40	7	105	239
2 ...	19	37	120	41	13	49	88
3 ...	22	91	124	42	10	45	79
4 ...	25	109	138	43	5	19	41
5 ...	38	103	122	44	2	11	27
6 ...	18	88	161	45	9	48	99
7 ...	10	46	95	46	24	152	150
8 ...	101	324	377	47	42	165	160
9 ...	58	211	270	48	178	553	458
10 ...	113	269	316	49	69	181	197
11 ...	51	154	238	50	222	1,015	391
12 ...	123	248	287	51	57	156	104
13 ...	292	279	345	52	12	52	99
14 ...	73	141	227	53	9	55	101
15 ...	66	154	345	54	35	78	173
16 ...	22	71	134	55	28	213	256
17 ...	15	48	107	56	33	116	150
18 ...	59	214	469	57	51	170	228
20 ...	45	150	314	58	21	50	142
21 ...	75	188	257	59	14	82	98
22 ...	19	74	72	60	11	104	201
23 ...	7	14	44	61	26	33	96
24 ...	148	321	304	62	33	301	336
25 ...	36	84	198	63	41	216	292
26 ...	15	40	119	64	144	388	505
27 ...	62	202	181	65	43	401	266
28 ...	124	290	594	66	67	303	421
29 ...	135	299	205	67	45	204	234
30 ...	23	75	184	68	48	282	418
31 ...	92	161	194	69	149	285	532
32 ...	24	83	101	70	12	72	78
33 ...	95	244	322	71	24	92	174
34 ...	20	31	51	72	35	108	148
35 ...	94	310	267	73	4	44	60
36 ...	51	67	106	74	16	54	110
37 ...	5	30	14	75	17	60	110
38 ...	39	159	167	76	3	40	57
39 ...	64	231	228	77	9	63	100

Total 1939-40—3,901
1940-41—12,291
1941-42—15,612

Correlation, that trees producing many brooms in the one year did so again in the next year.
1939-40 and 1940-41—r= +0.77
1940-41 and 1941-42 +0.73

would be considerably reduced, as would be the number of sporophores and consequently the intensity of infection. In addition the labour of removing brooms, if this is proved to be an economic control measure, would be considerably lessened. Conversely a tree with resistant pods only would be useless as severe fan- and cushion-broom production will sap its vitality and reduce its yield even if they do not eventually kill it. It is necessary to emphasise these points to avoid misconception and subsequent disappointment on the part of planters. Moreover, it is possible that trees showing resistance to fan- and cushion-brooms only might be useless in diseased areas for rehabilitation work and would only give satisfactory results when planted in large blocks. When scattered through existing cacao their disease avoidance might have little effect in protecting their pods which would be as severely infected as those on surrounding trees.

Information obtained during the past year on the production of diseased pods in this same plot of trees, though admittedly incomplete is of some interest. The results are summarised in Tables VI and VII. In all, 1,329 pods were

Table IV

Fan and Chupon Brooms—September, 1939 to September, 1942

Tree No.	Fan and Chupon Brooms			Tree No.	Fan and Chupon Brooms		
	1939-40	1940-41	1941-42		1939-40	1940-41	1941-42
1 ...	41	150	290	40	5	38	74
2 ...	16	25	82	41	8	32	68
3 ...	18	70	120	42	7	34	77
4 ...	20	86	115	43	4	10	25
5 ...	15	66	113	44	2	11	27
6 ...	18	74	152	45	7	27	86
7 ...	7	38	74	46	18	84	123
8 ...	49	151	189	47	12	28	97
9 ...	50	179	245	48	16	53	108
10 ...	33	79	143	49	38	109	160
11 ...	32	84	200	50	47	270	356
12 ...	82	155	240	51	28	79	92
13 ...	25	64	127	52	6	26	83
14 ...	46	106	195	53	4	39	68
15 ...	47	117	309	54	10	48	106
16 ...	14	44	110	55	18	153	202
17 ...	10	33	50	56	11	54	120
18 ...	11	45	76	57	48	141	192
20 ...	37	84	208	58	15	31	114
21 ...	54	128	184	59	5	40	55
22 ...	18	39	62	60	5	54	129
23 ...	7	14	44	61	22	22	59
24 ...	35	22	140	62	12	94	191
25 ...	31	67	174	63	4	20	53
26 ...	12	29	81	64	27	114	97
27 ...	38	73	104	65	11	74	146
28 ...	61	144	388	66	16	36	145
29 ...	30	88	113	67	35	132	216
30 ...	15	51	166	68	31	137	314
31 ...	33	89	147	69	74	175	290
32 ...	16	66	89	70	10	26	62
33 ...	64	172	300	71	18	64	143
34 ...	20	22	47	72	25	81	127
35 ...	64	182	231	73	4	33	59
36 ...	23	52	96	74	12	30	90
37 ...	2	24	14	75	16	56	99
38 ...	22	83	149	76	3	15	44
39 ...	34	77	104	77	9	61	85

Total 1939-40—1,793
1940-41—5,603
1941-42—10,253

Correlation, that trees producing many Fan and Chupon brooms in the one year did so again in the next year.

1939-40 and 1940-41—r= + 0.82
1940-41 and 1941-42— + 0.87

harvested of which 127, or 10 per cent. were attacked by witches' broom disease, 297 or 22 per cent. were destroyed by other diseases chiefly black pod (*Phytophthora palmivora*), and brown pod (*Botryodiplodia theobromae*) associated with damage by birds or animals. 905 pods or 68 per cent. were harvested in good condition. It is interesting to note that although witches' broom disease may now be classed as 'exceedingly severe' on this estate it only occasioned a direct loss of 10 per cent. of the pods which came to maturity. Since pods are attacked at any age some are lost before they come to maturity. No figures of this loss are available at present, but diseased cherelles were frequently observed. The indirect loss caused by damage to the trees is certainly considerable, but impossible to estimate. In 1942 the bulk of the crop avoided the disease because the wet season crop was low and the majority of the pods developed during dry weather when witches' broom disease infection was at a minimum. If the bulk of the crop had been set in August, September and October instead of in December, January and February, losses might have been much more severe. This advantage is offset by the fact that dry season pods may be 25-50 per cent. smaller than those ripened in the wet season.

Table V

Cushion Brooms—September, 1939 to September, 1942

Tree No.	Cushion Brooms			Tree No.	Cushion Brooms		
	1939-40	1940-41	1941-42		1939-40	1940-41	1941-42
1 ...	14	135	107	40	2	67	165
2 ...	3	12	38	41	5	17	20
3 ...	4	21	4	42	3	11	2
4 ...	5	23	23	43	1	9	16
5 ...	23	37	9	44	0	0	0
6 ...	0	14	9	45	2	21	13
7 ...	3	8	21	46	6	68	27
8 ...	52	173	188	47	30	137	63
9 ...	8	32	25	48	162	500	350
10 ...	80	190	173	49	31	72	37
11 ...	19	70	38	50	175	745	35
12 ...	41	93	47	51	29	77	12
13 ...	267	215	218	52	6	26	16
14 ...	27	35	32	53	5	16	33
15 ...	19	37	36	54	25	30	67
16 ...	8	27	24	55	10	60	54
17 ...	5	15	57	56	22	62	30
18 ...	48	169	393	57	3	29	36
20 ...	8	66	106	58	6	19	28
21 ...	21	60	73	59	9	42	43
22 ...	1	35	10	60	6	50	72
23 ...	0	0	0	61	4	12	37
24 ...	113	299	164	62	21	207	145
25 ...	5	17	24	63	37	196	239
26 ...	3	11	38	64	117	274	408
27 ...	24	129	77	65	32	327	120
28 ...	63	146	206	66	51	267	276
29 ...	105	211	92	67	10	72	18
30 ...	8	24	18	68	17	145	104
31 ...	59	72	47	69	75	110	242
32 ...	8	17	12	70	2	46	16
33 ...	31	72	22	71	6	28	31
34 ...	0	9	4	72	10	27	21
35 ...	30	128	36	73	0	11	1
36 ...	28	15	10	74	4	24	20
37 ...	3	6	0	75	1	4	11
38 ...	17	76	18	76	0	25	13
39 ...	30	154	124	77	0	2	15

Total 1939-40—2,108
1940-41—6,688
1941-42—5,359

Correlation, that trees producing many Cushion brooms in the one year did so again in the next year.

1939-40 and 1940-41—r = + 0.76
1940-41 and 1941-42— + 0.58

Table VI

Pods harvested from 76 trees January to October 1942

Date Harvested	Number Harvested	Per cent. Witches' Broom Disease
13/1/42	127	30
17/2/42	115	32
3/3/42	38	39
5/5/42	271	3
7/7/42	760	4
8/9/42	18	0
	1,329	10

It is unwise to draw too definite conclusions from one year's results, but there is no indication whatever of a positive correlation between the percentage of diseased pods per tree and either the total number of brooms (r=−0.08) or the number of cushion brooms (r = −0.13) per tree. This again suggests that an assumption that trees showing resistance to fan-brooms or to cushion-brooms will show pod resistance is unjustified.

Lastly, records of sporophore formation at River Estate have now been kept for over two years. The sporophore index (the number of sporophores which would be produced by a random sample of 100 brooms) is shown in Table VIII. There is a positive correlation (r = + 0.47**) between the sporophore index for a given week and the total number of brooms produced five weeks later. The fact that this correlation co-efficient came out as high as 0.47 in spite of other factors operating which include intensity of flush, intensity of flowering, climatic factors and particularly the known variation in

Table VII

Pods harvested January to October, 1942

Tree No.	Total Pods	Witches' Broom Disease Pods	Per cent. Witches' Broom Disease Pods	Tree No.	Total Pods	Witches' Broom Disease Pods	Per cent. Witches' Broom Disease Pods
1 ...	37	8	22	40	9	0	—
2 ...	23	1	4	41	33	2	6
3 ...	17	0	—	42	18	0	—
4 ...	33	0	—	43	0	0	—
5 ...	25	4	16	44	0	0	—
6 ...	18	1	5	45	1	0	—
7 ...	5	1	—	46	0	0	—
8 ...	20	1	5	47	15	1	7
9 ...	1	0	—	48	25	4	16
10 ...	27	2	7	49	10	1	10
11 ...	3	1	—	50	33	3	9
12 ...	16	4	25	51	0	0	—
13 ...	8	1	—	52	16	6	37
14 ...	14	1	7	53	25	1	4
15 ...	15	1	7	54	14	1	7
16 ...	12	5	42	55	18	1	5
17 ...	2	0	—	56	25	4	16
18 ...	6	1	—	57	35	2	6
20 ...	11	0	—	58	3	1	—
21 ...	89	8	9	59	8	0	—
22 ...	5	2	—	60	0	0	—
23 ...	0	0	—	61	48	5	10
24 ...	14	1	7	62	17	1	6
25 ...	50	1	2	63	22	1	4
26 ...	7	0	—	64	28	2	7
27 ...	48	1	2	65	14	0	—
28 ...	22	3	14	66	22	0	—
29 ...	10	1	10	67	2	0	—
30 ...	8	0	—	68	58	3	5
31 ...	47	12	25	69	42	0	—
32 ...	9	1	—	70	13	0	—
33 ...	9	1	—	71	1	0	—
34 ...	3	1	—	72	30	5	17
35 ...	38	9	24	73	1	0	—
36 ...	0	0	—	74	34	3	9
37 ...	0	0	—	75	14	0	—
38 ...	3	0	—	76	18	3	17
39 ...	18	4	22	77	4	0	—
			Totals ...	76	1,329	127	9.6

broom development after inoculation from about three weeks to about three months (five weeks is merely a convenient point near the mean) seems a strong indication that the supply of spores is a major controlling factor in this disease. It is of course possible that environmental conditions favourable for sporophore production are identical with those necessary for infection, which would accentuate any estimate of correlation between brooms and sporophores. A study of environmental and climatic factors will be a logical corollary to these investigations.

Table VIII

Sporophore Index—August, 1940 to September, 1942

Week Ending	Sporophore Index *	Week Ending	Sporophore Index	Week Ending	Sporophore Index
6/ 8/40 ...	—	6/ 5/41 ...	1	3/2/42 ...	12
13/ 8/40 ...	—	13/ 5/41 ...	—	10/2/42 ...	10
20/ 8/40 ...	2	20/ 5/41 ...	—	17/2/42 ...	12
27/ 8/40 ...	4	27/ 5/41 ...	3	24/2/42 ...	7
3/ 9/40 ...	2	3/ 6/41 ...	134	3/3/42 ...	15
10/ 9/40 ...	5	10/ 6/41 ...	50	10/3/42 ...	4
17/ 9/40 ...	7	17/ 6/41 ...	35	17/3/42 ...	1
24/ 9/40 ...	2	24/ 6/41 ...	15	24/3/42 ...	—
				31/3/42 ...	1
1/10/40 ...	4	1/ 7/41 ...	22		
8/10/40 ...	—	8/ 7/41 ...	22	7/4/42 ...	—
15/10/40 ...	64	15/ 7/41 ...	17	14/4/42 ...	—
22/10/40 ...	136	22/ 7/41 ...	24	21/4/42 ...	—
29/10/40 ...	36	29/ 7/41 ...	2	28/4/42 ...	—
5/11/40 ...	88	5/ 8/41 ...	3	5/5/42 ...	16
12/11/40 ...	140	12/ 8/41 ...	56	12/5/42 ...	25
19/11/40 ...	256	19/ 8/41 ...	41	19/5/42 ...	20
28/11/40 ...	36	26/ 8/41 ...	19	26/5/42 ...	10
3/12/40 ...	7	2/ 9/41 ...	2	2/6/42 ...	153
10/12/40 ...	147	9/ 9/41 ...	18	9/6/42 ...	9
17/12/40 ...	57	16/ 9/41 ...	6	16/6/42 ...	58
24/12/40 ...	159	23/ 9/41 ...	55	23/6/42 ...	16
31/12/40 ...	290	30/ 9/41 ...	290	30/6/42 ...	34
7/ 1/41 ...	154	7/10/41 ...	93	7/7/42 ...	37
13/ 1/41 ...	11	17/10/41 ...	180	14/7/42 ...	29
20/ 1/41 ...	41	24/10/41 ...	126	21/7/42 ...	6
27/ 1/41 ...	50	28/10/41 ...	140	28/7/42 ...	21
3/ 2/41 ...	9	3/11/41 ...	89	4/8/42 ...	16
10/ 2/41 ...	14	10/11/41 ...	69	11/8/42 ...	38
17/ 2/41 ...	13	17/11/41 ...	50	18/8/42 ...	10
25/ 2/41 ...	9	24/11/41 ...	96	25/8/42 ...	3
4/ 3/41 ...	—	2/12/41 ...	177	1/9/42 ...	59
11/ 3/41 ...	—	9/12/41 ...	410	8/9/42 ...	29
18/ 3/41 ...	4	16/12/41 ...	162	15/9/42 ...	56
25/ 3/41 ...	—	23/12/41 ...	111	22/9/42 ...	142
		30/12/41 ...	80	29/9/42 ...	159
1/ 4/41 ...	6				
8/ 4/41 ...	1	6/ 1/42 ...	174		
15/ 4/41 ...	2	12/ 1/42 ...	22		
22/ 4/41 ...	4	19/ 1/42 ...	45		
29/ 4/41 ...	1	26/ 1/42 ...	8		

* Number of sporophores produced per week by a random sample of one hundred Fan and Cushion brooms.

Summary

1. Observations on witches' broom disease made at River Estate, Diego Martin, Trinidad, from 1939-1942 are discussed.
2. During the three years of the investigation the disease has rapidly increased in severity, and although by 1942 certain trees had begun to show signs of considerable damage, there is no reason to believe that it has reached its maximum intensity.
3. Variation in the number of brooms produced per tree per annum is very great, but it was established that trees which produce many brooms one year are likely to do so again the next year and that trees which produce only a few brooms are likely to behave similarly the next year. This applies both to fan- and cushion-brooms.
4. Cushion-brooms and flower production are closely correlated, but there is no such relationship between fan-brooms and flush; nor are cushion-brooms and fan-brooms per tree closely correlated. It is suggested that these figures indicate that if there is any form of resistance to the disease to be found in Trinidad cacao it is not likely to be an inherent protoplasmic one but more probably some form of disease-avoidance in the vegetative tissues of certain trees. It does not follow that a tree which shows resistance to fan-brooms will show any comparable resistance to cushion-brooms or to pod infection.
5. For reasons stated it is considered that even trees showing resistance to fan-brooms alone would be of considerable value in the control of the disease.
6. Although the disease could be classed as 'exceedingly severe' in 1942, pod infection was only 10 per cent. because the bulk of the crop matured in the dry season when the disease was at a minimum. No positive correlation was found either between the percentage of diseased pods per tree and fan-brooms per tree or total brooms per tree.
7. Figures obtained for the formation of sporophores on this estate indicate that the supply of spores is a major controlling factor in this disease.

Acknowledgments

I am indebted to the Trinidad Department of Agriculture and especially to the Manager of River Estate for their constant help during these investigations. Much of the field work was carried out by Messrs. S. H. Crowdy and R. K. McKee, Lecturers in Mycology at the Imperial College of Tropical Agriculture.

Reference

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STUDIES ON THE PROPAGATION OF THE MANGO

Among a large number of interesting aspects of the propagation methods of the mango studied at the Kodur Fruit Research Station (Cuddapah District, Madras), the matter of eliminating variations from root stocks and ensuring uniformity therein, has been receiving much attention (B.G. Naik, *Ind. Jour. Agr. Sc.* 11, Pt. 5). The mango being ordinarily a cross-fertilised plant gives rise to a progeny of plants of mixed characteristics. The seedlings ordinarily used as stocks for grafting upon, are therefore not at all uniform and as the characters induced by the stock in the resulting graft are concerned, the latter are of uncertain and of varying merit. One method by which it has been attempted to overcome this difficulty is by making use of the polyembryonic varieties which produce seed, the seedlings from which are so uniform in character that they may be regarded as possessing no fertilised embyro at all. Acting upon this fact, work has related to the testing of seeds from several trees found in Malabar and South Canara which are believed to be polyembryonic. It is reported that some of these seeds gave as many as five seedlings while a large number produced two, three and four seedlings each. It was also noted that though the percentage of germination was rather low in these varieties, which is also the common belief, still at least two varieties were free from this drawback and showed a germination percentage varying from 55 to 66.

Attempts were also made to secure uniformity in stock by the method of root-grafting, with very gratifying results. Despite the limitations of this method as compared with other methods like, for example, inarching, considerable success has been obtained, about 23 per cent. of the root grafts having successfully taken. It is however within our experience that the initial successes do not last and that in the course of a year or so the grafted plants die off after they are planted out in their permanent places. These present results will therefore have to be watched as to their behaviour after planting out.

The effect of sowing mango seeds with the suture pointing upwards or downwards, sowing shelled seeds, sowing seeds graded into different sizes, and different methods of budding and grafting all form part of these studies and results of much practical value are reported.—(*Current Science*, 11, No. 4, 1942.)

STUDIES ON AERATION OF CACAO SOILS IN TRINIDAD (III)

BY

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INTRODUCTION

By F. Hardy

(*Professor of Chemistry and Soil Science*)

The first two articles of this series (1, 2) dealt with the bulk of the data and the deductions derived therefrom pertaining to studies on soil aeration in cacao fields that were conducted in Trinidad during 1939-1941 by Dr. H. Vine and Mr. H. A. Thompson, former Post-Graduate Students of the College. During the course of their field work, but not as part of the main researches, both investigators attempted on a few occasions to measure the rate of escape of carbon-dioxide gas from the soil surface at various cacao sites, but beyond stating the results obtained, their data were not further considered because of preoccupation with other more urgent problems and lack of time. It is intended in this article to discuss the significance of the evidence which was obtained in these preliminary "soil respiration" studies, and to try to draw further deductions regarding soil aeration at the sites briefly investigated. The writer is solely responsible for the conclusions which have been reached and for recommendations based on them.

PART III

GASEOUS DIFFUSION IN CERTAIN CACAO SOIL-TYPES IN TRINIDAD

BY

F. Hardy

Methods for measuring the "soil respiration rate" were first of all briefly investigated by Dr. Vine (3). Bell-jars or inverted cans were pressed into the soil surface and the gas that diffused out of the soil within a suitable time period (usually four hours) was collected in bottles or in standard solutions of caustic soda contained in small dishes exposed within the vessels. Subsequently the carbon-dioxide contents of the gaseous samples or soda solutions were determined in the laboratory by gas analysis or by titration with standard acid. The soda absorption method proved to be the simpler, and it was consequently employed later by Mr. Thompson for procuring periodic data at the four sites that had been selected for investigating soil-gas composition, as described in the last article (2).

Dr. Vine's results were expressed as means of six or eight replicates, and their statistical analysis demonstrated that significant differences occurred between the rates of escape of carbon-dioxide from the soil surface on different days when the soil contained different amounts of moisture, being somewhat higher in his experiments for relatively moist soil than for dry.

The numerical values obtained by Dr. Vine and those procured later by Mr. Thompson for rate of soil respiration may be compared with results recorded by Dr. E. Buckingham (a pioneer in soil aeration investigations), formerly Soil Physicist at the Bureau of Soils of the United States Department of Agriculture in Washington, D.C., who published a bulletin on his work in 1904 (4). Buckingham experimentally investigated the passage of carbon-dioxide from the soil into the atmosphere and its replacement by oxygen, as affected by soil texture, structure and compactness, and by barometric pressure, air temperature and soil-gas composition. From his data and certain mathematical deductions derived therefrom, Buckingham concluded that, among the various agencies controlling the escape of carbon-dioxide from the soil and its replacement by oxygen, simple *diffusion* is the most effective, all other agencies having but minor significance. He showed that *the rate of diffusion of carbon-dioxide outwards from a soil is proportional to the square of the gross pore-space, and is independent of the actual dimensions of the pores themselves**. He constructed a table based on this relationship, in which the change in concentration of carbon-dioxide with depth and the rates of escape of the gas and its replacement by oxygen is shown for various porosities of soil. From Buckingham's data, expressed in graphical form, the values in Table I have been derived by the writer, following the procedure used by Keen (5).

In Table I, the outward diffusion of carbon-dioxide from the soil is stated as volume in litres of the gas which escapes at each square metre of surface in one day, when the temperature and pressure of the atmosphere are 77°F or (25°C) and 760 mm. of mercury respectively. The magnitude of this volume for any given porosity is naturally greater the larger the concentration gradient of carbon-dioxide. The values given in the table for increasing gradients are therefore arranged in columns representing pore-space increments of 10 per cent.

* This important result accords with the earlier findings of H. T. Brown and F. Escombe (*Phil. Trans.*, 1900, 193B, p. 223), who proved that the rate of diffusion of gases through small pores is not proportionally less than through larger holes, but is governed by the total cross-sectional area of the pore-space rather than by the size of the individual pores (*See* E. J. Russell, "*Soil Conditions*", 1932, p. 449).

Table I

Relationship between Soil Porosity, Diffusion of Carbon-dioxide and its Concentration at different Depths

(*After B. A. Keen, from E. Buckingham*)

Carbon-dioxide concentration gradient (Per cent. per cm.)	Effective Porosity of Soil: 10 %	20 %	30 %	40 %	50 %	60 %	70 %
	Diffusion Rate: Quantity of carbon-dioxide diffusing to soil surface (Litres per square metre per day; 77°F and 760 mm.)						
0.01	0.2	0.7	1.4	2.7	4.0	5.9	8.3
0.02	0.4	1.3	2.9	5.3	8.1	11.4	15.8
0.03	0.6	1.9	4.4	7.8	12.2	17.2	23.4
0.04	0.8	2.5	5.9	10.3	16.2	23.0	31.0
0.05	1.1	3.1	7.3	13.0	20.2	28.8	38.6
0.06	1.3	3.7	8.8	15.5	24.2	34.7	46.4
0.07	1.5	4.4	10.2	18.0	28.2	40.6	54.0
0.08	1.7	5.1	11.6	20.5	32.0	46.5	61.6
0.10	2.1	6.4	14.6	25.5	40.4	57.3	77.0
0.12	2.5	7.7	17.4	30.7	48.5	68.2	92.5
0.14	2.9	9.0	20.3	35.7	56.5	79.4	108.0

The table may be used in several ways for deducing the conditions of aeration within a soil. For example, suppose the average porosity of a soil is known and the percentage of carbon dioxide at a certain depth has been determined, then the amount of carbon-dioxide escaping at the surface may be deduced by inspection of the table or by the use of graphs constructed from the data included therein. Or again, suppose that the porosity is known and the rate of diffusion to the soil surface has been measured, then the concentration of carbon-dioxide at any desired depth may readily be deduced. Finally, when both carbon-dioxide diffusion and carbon-dioxide concentration at one or more depths have been measured, then Buckingham's table may be used for deducing the "effective porosity" of the soil.

This last procedure has been applied by the writer to the experimental data recorded by Dr. Vine and Mr. Thompson in a further attempt to procure information concerning soil porosity within certain cacao sites under different moisture conditions. It should be noted that the temperature just below the soil surface at the sites where the gas samples were collected varied only by about one-half of a degree around a mean of 76°F., which is nearly identical with the temperature (77°F) to which Buckingham's data actually refer, so that no temperature corrections need be made in the compilations.

(A) River Fine Sand: River Estate

The rate of escape of carbon-dioxide at this site was measured by Dr. Vine on three separate occasions during the wet seasons of 1939 and 1940, and once in the dry season of 1940. On each occasion except one the carbon-dioxide content at the 10 cm. depth within the soil profile was also measured, and on three occasions, at the 20 or 30 cm. depths as well (*see* Part II; Table II). The porosity of the soil near the site of the gas collections had previously been determined, and gross soil-moisture contents were known for each sampling occasion. The relevant data are brought together in Table II, compiled from Dr. Vine's dissertation (3).

Explanation

In Table II, Column 2 gives the gas analysis data for samples collected at different depths, from which the carbon-dioxide concentration gradients are calculated (Column 3). In Column 4 are presented the effective pore-space values corresponding to each gradient, derived by interpolation in graphs based on Buckingham's table (Table I), knowing the rate of carbon-dioxide production at the soil surface from actual determinations made at the same time. In Columns 5 and 6 are given the capillary and non-capillary pore-space values for the site as previously recorded (*see* Part I: Table IV). In Column 7 is given the pore-space occupied by water at the time of sampling, and in Column 8 the pore-space volume occupied by air. The last column gives the percentage of the total pore-space which was occupied by water at the time of sampling.

Note.—It should be noted that *capillary* pore-space is derived from index of texture and apparent specific gravity values for the soil of the different layers, in accordance with a suggestion originally made by Dr. Vine (6). This procedure, however, may provide only a rough measure of capillary pores, which are arbitrarily defined as those having diameters less than 0.01 mm., though it probably assesses fairly accurately the water associated with the soil colloidal matter. (*See* part I.) The *non-capillary* pore-space is obtained by subtracting the capillary pore-space values from the total pore-space, determined by drying and weighing soil-cores procured by means of a special soil-sampling tube having a known constant volume.

Results

The values for effective pore-space (Column 4, Table II), derived from gas-analysis data, are relatively low throughout. Small values were obtained at the 10 cm. depth on the first two dates of sampling during the wet season of 1939 when the moisture content of the soil was high (Columns 7 and 9). At the 30 cm. depth on the second occasion, the deduced effective pore-space value was appreciably larger, namely, 16 per cent. On the third sampling occasion, in the middle of the dry season of 1940, the effective pore-space was about the same, though carbon-dioxide production had fallen considerably. Unfortunately no carbon dioxide concentration values are available for the last occasion when the respiration rate was measured; by this time the soil had become wetter again and the respiration rate had increased greatly.

Table II

Diffusion of Carbon-Dioxide and Effective Pore-Space For River Fine Sand Cacao Soil-type

(*Experimental Data by H. Vine*)

1	2	3	4	5	6	7	8	9
				Soil porosity data at time of Sampling				
Sampling depth	Carbon-dioxide concentration	Carbon-dioxide gradient	Effective pore-space	Capillary pore-space	Non-capillary pore-space	Pore-space occupied by :— (*a*) Water	(*b*) Air	Degree of saturation of pore-space by water
(cm.)	(Vol. per cent.)	(Per cent. per cm.)	(Vol. per cent.)	(Vol. per cent.)		(Vol. per cent.)		(Vol. per cent.)
				River Estate				
	(1) *November* 24, 1939 : CO_2 diffusion, 8.1 litres per sq. metre per day							
(A) 10 cm.	3.0	0.300	11	28	21	41	8	84
(B) 10 cm.	3.9	0.390	9	28	21	41	8	84
	(2) *December* 8, 1939 : CO_2 diffusion, 5.7 litres per sq. metre per day							
(A) 10 cm.	3.4	0.340	9	28	21	41	8	84
(B) 10 cm.	4.4	0.440	9	28	21	41	8	84
30 cm.	3.9	0.130	16	35	10	38	7	84
	(3) *March* 1, 1940 : CO_2 diffusion, 3.8 litres per sq. metre per day							
(A) 10 cm.	1.1	0.110	14	28	21	29	20	59
20 cm.	1.4	0.070	17	35	10	28	17	62
	(4) *July* 2, 1940 : CO_2 diffusion, 9.6 litres per sq. metre per day							
(A) 10 cm.	—	—	—	28	21	38	11	77
20 cm.	—	—	—	35	10	35	10	77

Conclusions

On the whole, the derived values for effective pore-space (Column 4) are of the same order of magnitude as the values for pore-space occupied by air at the time of sampling (Column 8). Evidently, during the wet season at the River Estate site, the soil may become so replete with water that the size of the pores within which gas diffusion may proceed is reduced to very small magnitude. This finding accords well with conclusions based on other experimental evidence presented and discussed in Parts I and II of this series of articles.

(B) Gaseous Diffusion at other Cacao Sites

The rate of escape of carbon-dioxide was also measured at the River Estate site by Mr. Thompson on four occasions during the dry season of 1941, and at the three other sites where soil-gas composition, soil moisture content and soil porosity were being followed, at various times with the same period. These extra sites, as before, were (A) College Botany Plot, (C) La Reconnaissance (L.R.C.) Estate (both comprising fine sandy soil), and (D) Las Hermanas Estate, consisting of heavy clay soil. The data for carbon-dioxide contents obtained by Mr. Thompson at River Estate are more abundant than the preliminary set procured by Dr. Vine, and on nearly all occasions they included values for five different depths, namely, 4, 10, 18, 36 and 48 inches (or 10, 25, 45, 90 and 120 cm.). The complete data reported by Mr. Thompson (7) are brought together in Table III.

Explanation

The data in Table III are arranged on the same plan as those in the table before. It may be noticed that Mr. Thompson's porosity values (Columns 5 and 6) for the River Estate site are slightly different from those employed by Dr. Vine. This fact is explained by soil heterogeneity ; the two sites, though in the same cacao field, being some distance apart. Porosity data for the Las Hermanas site (the only clay site) were procured when the soil was moist and plastic. The soil below the 10-inch (25 cm.) depth at that time was evidently quite devoid of air, its pore-space being entirely capillary ; all its moisture was presumably held colloidally.

At each site, the pore-space volumes occupied by water and by air at the times of sampling (Columns 7 and 8) are approximately known only for the first two depths (0-4 and 4-10 inches). The soil-moisture data on which the estimates were made actually refer to the 0-6 and 6-12 inch layers, but the error involved in assuming that they would equally well apply to the shallower depths is not great.

Table III

Diffusion of Carbon-dioxide and Effective Pore-space for Four Different Cacao Sites

(*Experimental Data by H. A. Thompson*)

1	2	3	4	5	6	7	8	9
				Soil Porosity data at time of Sampling				
Sampling depth	Carbon-dioxide concentration	Carbon-dioxide gradient	Effective pore-space	Capillary pore-space	Non-Capillary pore-space	Pore-space occupied by :— (*a*) Water	(*b*) Air	Degree of saturation of pore-space by water
(cm.)	(Vol. per cent.)	(Per cent. per cm.)	(Vol. per cent.)	(Vol. per cent.)		(Vol. per cent.)		(Vol. per cent.)
				(A) College Plot				
				(1) *February* 18, 1941 : CO_2 diffusion, 4.66 litres per sq. metre per day				
10 cm. ...	0.4	0.040	26	28	19	22	25	47
25 ,, ...	0.9	0.036	28	30	16	22	24	52
45 ,, ...	1.4	0.031	31	24	16	—	—	—
90 ,, ...	3.6	0.040	26	23	16	—	—	—
120 ,, ...	4.1	0.034	28	18	20	—	—	—
				(2) *March* 4, 1941 : CO_2 diffusion, 1.90 litres per sq. metre per day				
10 cm. ...	0.2	0.020	23	28	19	17	30	36
25 ,, ...	0.7	0.028	20	30	16	22	24	48
45 ,, ...	1.3	0.029	20	24	16	—	—	—
90 ,, ...	2.7	0.030	20	23	16	—	—	—
120 ,, ...	—	—	—	18	20	—	—	—
				(B) River Estate				
				(1) *February* 11, 1941 : CO_2 diffusion, 7.15 litres per sq. metre per day				
10 cm. ...	1.2	0.120	19	26	23	35	14	71
25 ,, ...	2.5	0.100	21	31	13	33	11	75
45 ,, ...	5.0	0.111	21	30	6	—	—	—
90 ,, ...	7.7	0.086	23	26	10	—	—	—
120 ,, ...	9.0	0.075	24	28	13	—	—	—
				(2) *February* 25, 1941 : CO_2 diffusion, 7.93 litres per sq. metre per day				
10 cm. ...	0.9	0.090	23	26	23	32	17	65
25 ,, ...	1.8	0.072	26	31	13	34	10	77
45 ,, ...	3.7	0.082	24	30	6	—	—	—
90 ,, ...	5.8	0.065	27	26	10	—	—	—
120 ,, ...	8.0	0.067	27	28	13	—	—	—
				(3) *April* 23, 1941 : CO_2 diffusion, 20.4 litres per sq. metre per day				
10 cm. ...	0.5	0.050	50	26	23	31	18	63
25 ,, ...	1.2	0.048	53	31	13	31	13	70
45 ,, ...	2.3	0.051	50	30	6	—	—	—
90 ,, ...	3.7	0.041	56	26	10	—	—	—
120 ,, ...	5.0	0.042	55	28	13	—	—	—
				(4) *May* 27, 1941 : CO_2 diffusion, 15.1 litres per sq. metre per day				
10 cm. ...	0.5	0.050	43	26	23	32	17	65
25 ,, ...	1.2	0.048	44	31	13	33	11	75
45 ,, ...	2.0	0.045	45	30	6	—	—	—
90 ,, ...	3.6	0.040	48	26	10	—	—	—
120 ,, ...	5.3	0.044	45	28	13	—	—	—

Table III—*Continued.*

1	2	3	4	5	6	7	8	9
				Soil Porosity data at time of Sampling				
Sampling depth (cm.)	Carbon-dioxide concentration (Vol. per cent.)	Carbon-dioxide gradient (Per cent. per cm.	Effective pore-space (Vol. per cent.)	Capillary pore-space (Vol. per cent.)	Non-Capillary Pore-space (Vol. per cent.)	Pore-space occupied by :— (*a*) Water (Vol. per cent.)	(*b*) Air (Vol. per cent.)	Degree of saturation of pore-space by water (Vol. per cent.)
				(C) La Reconnaissance Estate				
				(1) *February* 13, 1941 : CO_2 diffusion, 6.98 litres per sq. metre per day				
10 cm. ...	3.5	0.350	11	36	11	42	5	89
25 ,, ...	4.5	0.180	15	30	10	37	3	93
45 ,, ...	6.3	0.140	13	32	8	—	—	—
90 ,, ...	5.6	0.062	26	20	18	—	—	—
120 ,, ...	3.7	0.031	37	18	22	—	—	—
				(2) *February* 27, 1941 : CO_2 diffusion, 7.25 litres per sq. metre per day				
10 cm. ...	—	—	—	36	11	36	11	77
25 ,, ...	1.2	0.048	30	30	10	34	6	85
45 ,, ...	3.6	0.080	24	32	8	—	—	—
90 ,, ...	5.9	0.066	26	20	18	—	—	—
120 ,, ...	3.8	0.032	37	18	22	—	—	—
				(3) *March* 13, 1941 : CO_2 diffusion, 6.94 litres per sq. metre per day				
10 cm. ...	1.3	0.130	19	36	11	35	12	74
25 ,, ...	1.3	0.052	28	30	10	36	4	90
45 ,, ...	2.5	0.055	28	32	8	—	—	—
90 ,, ...	3.9	0.043	31	20	18	—	—	—
120 ,, ...	3.9	0.033	39	18	22	—	—	—
				(4) *April* 24, 1941 : CO_2 diffusion 21.7 litres per sq. metre per day				
10 cm. ...	0.1	0.010	—	36	11	27	20	57
25 ,, ...	0.7	0.028	70	30	10	29	11	73
45 ,, ...	1.3	0.029	69	32	8	—	—	—
90 ,, ...	3.2	0.035	63	20	18	—	—	—
120 ,, ...	3.8	0.032	67	18	22	—	—	—
				(5) *May* 27, 1941 : CO_2 diffusion, 14.8 litres per sq. metre per day				
10 cm. ...	0.2	0.020	68	36	11	29	18	62
25 ,, ...	0.8	0.032	53	30	10	29	11	73
45 ,, ...	1.4	0.031	53	32	8	—	—	—
90 ,, ...	3.6	0.040	48	20	18	—	—	—
120 ,, ...	4.5	0.038	49	18	22	—	—	—
				(D) Las Hermanas Estate				
				(1) *February* 20, 1941 : CO_2 diffusion, 5.72 litres per sq. metre per day				
10 cm. ...	1.2	0.120	18	50	7	35	22	61
25 ,, ...	1.6	0.064	24	50	5	35	20	64
45 ,, ...	3.9	0.086	21	49	0	—	—	—
90 ,, ...	3.5	0.039	30	46	0	—	—	—
120 ,, ...	—	—	—	44	0	—	—	—
				(2) *March* 5, 1941 : CO_2 diffusion, 5.30 litres per sq. metre per day				
10 cm. ...	0.2	0.020	40	50	7	29	28	51
25 ,, ...	1.0	0.040	28	50	5	32	23	58
45 ,, ...	1.2	0.027	35	49	0	—	—	—
90 ,, ...	12.0	0.133	16	46	0	—	—	—
120 ,, ...	—	—	—	44	0	—	—	—

RESULTS

(*A*) COLLEGE PLOT. Only two determinations were here attempted; the data refer solely to drying conditions during the dry season when the soil was less than half saturated by water. Diffusion of carbon-dioxide to the soil surface was much less on the second occasion when the soil was drier, mainly because the actual production of the gas within the soil was smaller, giving a lower concentration gradient. On neither occasion was the moisture content of the soil sufficient even to fill the capillary pore-space (Column 7), so that the free air-space within the soil was exceptionally large (Column 8). The data show that this soil, on the two occasions when it was tested, was highly porous and well-aerated, a conclusion which is supported by previous evidence based on soil-gas analysis (2). Carbon-dioxide production, though relatively small in quantity, was quite uniform at all the depths at which gas samples were taken, so that the concentration gradients were steady.

(*B*) RIVER ESTATE. The four determinations of diffusion rate made here by Mr. Thompson were all carried out in the dry season of 1941; they therefore augment the wet season determinations made by Dr. Vine. In order to render comparison easier, all the relevant information for the surface 4-inch (10 cm.) layer is brought together in Table IV, in which the gas data are arranged in order of decreasing soil moisture content.

Table IV

Diffusion of Carbon-dioxide and Effective Pore-space: Summarised Data for Surface Soil-layer at Four Different Cacao Sites

Thickness of Soil Layer, 10 cm. (or 4 inches)

1	2		3		4	5	6	7
Date of sampling	Soil porosity (*a*) Capillary. (Vol. per cent.)	(*b*) Non-capillary. (Vol. per cent.)	Pore-space occupied by :— (*a*) Water (Vol. per cent.)	(*b*) Air	Carbon-dioxide gradient (Average values). (Per cent. per cm.)	Diffusion rate of carbon-dioxide (Litres per sq. metre per day).	Effective pore-space (Vol. per cent.)	Degree of saturation of pore-space by water at time of sampling. (Vol. per cent.)
(A) COLLEGE PLOT								
Dry Season (H. A. Thompson)								
Feb. 18, 1941...	28	19	22	25	0.038	4.66	27	47 (dry)
Mar. 4, ,, ...	28	19	17	30	0.027	1.90	21	36 (v. dry)
(B) RIVER ESTATE								
Wet Season (H. Vine)—Means of Pairs.								
Nov. 24, 1939...	28	21	41	8	0.345	8.10	10	84 (wet)
Dec. 8, ,, ...	28	21	41	8	0.390	5.70	9	84 (wet)
Dry Season (H. A. Thompson)								
Feb. 11, 1941...	26	23	35	14	0.098	7.15	21	71 (moist)
Feb. 25, ,, ...	26	23	32	17	0.075	7.93	25	65 (f. moist)
May 27, ,, ...	26	23	32	17	0.045	15.10	45	65 (f. moist)
Apr. 23, ,, ...	26	23	31	18	0.046	20.40	52	63 (f. moist)
Dry Season (H. Vine)								
Mar. 1, 1940...	28	21	29	20	0.110	3.80	15	59 (f. dry)
(C) LA RECONNAISSANCE ESTATE								
Dry Season (H. A. Thompson)								
Feb. 13, 1941...	36	11	42	5	0.127	6.98	18	89 (v. wet)
Feb. 27, ,,	36	11	36	11	0.056	7.25	28	77 (moist)
Mar. 13, ,, ...	36	11	35	12	0.046	6.94	30	74 (moist)
May 27, ,, ...	36	11	29	18	0.035	14.80	48	62 (f. moist)
Apr. 24, ,, ...	36	11	27	20	0.031	21.70	68	57 (f. dry)
(D) LAS HERMANAS ESTATE								
Dry Season (H. A. Thompson) :								
Feb. 20, 1941...	50	7	35	22	0.063	5.72	23	61 (v. dry)
Mar. 5, ,, ...	50	7	29	28	0.029	5.30	33	51 (v. dry)

It will be observed in Table IV (Column 7) that the pore-space occupied by water in the surface soil-layer at the River Estate site ranged from 84 per cent. of the total pore-space volume in the wet season to 59 per cent. in the dry season, both of which values represent volumes greater than the capillary pore-space, implying that the non-capillary pores were never entirely depleted of water, not even by the end of the dry season. The combined gas data show that, as the soil dried out, the content of carbon-dioxide in the upper 4-inch layer diminished rapidly (from nearly 4 per cent. recorded by Dr. Vine in the wet season, to about 0.5 per cent. recorded by Mr. Thompson at the end of the dry season). This rapid diminution may partly be attributed to a gradual cessation of biological activity. It was evidently accompanied by a marked increase in the effective pore-space caused by the removal of water. The rate of increase in amount of effective pore-space apparently became suddenly exaggerated towards the end of the dry season of 1941, as indicated by a greatly enhanced diffusion rate of carbon-dioxide. This unexpected result may be explained on the assumption that minute *cracks* developed as the soil dried out, though such an explanation could not unreservedly be accepted without much further experimental evidence. It is noteworthy that no such indication of soil cracking is revealed by Dr. Vine's single dry season value. The phenomenon is explained differently by Mr. Thompson as an effect of occasional heavy showers of rain which fell during late April and May, wetting the superficial accumulation of leaf-litter, and initiating a sudden onset of biological activity.

The normal production of carbon-dioxide within the soil profile at the River Estate site was evidently fairly uniform at different depths, though it tended to be higher in the upper layers where the content of soil organic matter presumably is greatest. It was considerably higher for comparable pore-space values than at the College site.

(*C*) La Reconnaissance Estate. Five determinations of diffusion rate were made at this site by Mr. Thompson during the dry season of 1941. On the first three occasions, the soil was still very moist, and it did not really begin to dry out until early April. As at the River Estate site, carbon-dioxide concentration in the surface 4-inch layer diminished rapidly (from 1.3 to 0.3 per cent.) as the soil dried, and similarly also, diffusion of the gas increased abnormally rapidly after all the non-capillary and some of the capillary soil-moisture had evaporated. This last result may again be explained by assuming that *soil cracks* developed, thus greatly augmenting the effective pore-space of the soil. The distribution of carbon-dioxide at the La Reconnaissance site was very irregular within the profile as compared with the last two sites, being much higher in the upper layers in all cases except when the soil was dry, implying a higher biological activity there, or an irregular pore-space distribution. Production of carbon-dioxide was about the same for comparable pore-space values as at the River Estate site.

(*D*) Las Hermanas Estate. Only two complete sets of data were procured by Mr. Thompson at this clay site, each when the soil was relatively very dry, and a large proportion of the capillary pore-space, as well as all the non-capillary pore-space, had been depleted of water. In spite of extreme dryness, the diffusion rates were not unusually great, nor were the derived effective pore-space values abnormally large. Thus soil cracking need not be postulated to explain the dry season results for this soil; evidently the finer pores which comprise the capillary pore-space freely allowed gaseous diffusion to proceed once water had been removed from them, and this seemed to apply also to layers below the 4-inch (10 cm.) depth. The Las Hermanas clay soil develops sporadic *wide* cracks during dry weather, but the cracking referred to in these notes is the very fine cracking that is almost invisible to the naked eye.

The production of carbon-dioxide at the Las Hermanas site was apparently very irregular, but the meagre data render detailed consideration unwarranted. On the whole, it tended to be less than that at the last two sites.

Soil Organic Matter and Acidity Status at the Four Sites

For purposes of comparison, the contents of organic matter and nitrogen and carbon-nitrogen ratios, and the degree of soil acidity are set out in Table V for each of the cacao sites.*

The sampling depths of the organic profiles were not the same as those employed for gas sampling, but they serve to indicate the main differences between the four sites. Of the three sandy sites, the College site shows the highest organic matter and nitrogen status and the widest carbon-nitrogen ratios, but the degree of acidity is extremely high (average pH, 4.6). This highly acidic condition might be supposed to interfere with the normal activity of nitrifying bacteria, which are believed to operate best at reactions near neutrality (pH 7.0). Though no attempt was made to assess the bacterial numbers in the various soil layers, it would be expected that biological breakdown of organic matter and the oxidation of carbon would be most tardy at the College site. This conclusion is supported by the relatively low rate of production of carbon-dioxide at this site, alluded to in the last section. The organic status of the River Estate site seems to be only slightly superior to that of the La Reconnaissance Estate site; the distribution of organic matter and nitrogen is perhaps more regular

* The data in Table V are not the same as those reported by Mr. H. A. Thompson but are based on re-determinations, employing standard depths of sampling, designed to render comparison easier.

Table V

Soil Organic Matter Status and Acidity at the Four Cacao Sites

Depth. (inches)	(A) College				(B) River Estate				(C) L.R.C. Estate				(D) Las Hermanas Estate			
	Organic matter. %	Total nitrogen %	C/N ratio	pH	Organic matter. %	Total nitrogen %	C/N ratio	pH	Organic matter. %	Total nitrogen %	C/N ratio	pH	Organic matter. %	Total nitrogen %	C/N ratio	pH
0-3	4.9	0.26	11.0	4.8	2.3	0.15	8.7	6.6	2.1	0.14	8.8	6.0	5.4	0.33	9.4	6.7
3-6	2.3	0.17	7.7	4.5	1.5	0.11	7.8	6.9	3.0	0.20	8.5	6.3	2.5	0.22	6.5	5.8
6-12	1.5	0.12	7.1	4.3	1.1	0.10	6.3	7.0	1.2	0.10	6.9	6.4	1.2	0.14	4.9	4.9
12-18	1.1	0.10	6.3	4.6	0.9	0.09	5.7	6.4	0.6	0.07	4.9	5.8	0.9	0.12	4.3	4.9
18-24	0.6	0.09	3.9	4.7	0.8	0.07	4.2	6.0	0.5	0.06	4.9	5.6	0.8	0.11	4.2	4.8
Weighted means 0-24 ins. ...	1.7	0.13	7.4	4.6	1.2	0.10	6.3	6.5	1.2	0.10	7.0	6.0	1.7	0.16	6.1	5.2

there, and the degree of acidity is less. The La Reconnaissance Estate soil contains a greater amount of organic matter in the surface six inches. The organic status of the Las Hermanas Estate clay-soil site differs from that at the three sandy sites in as much as the organic matter is mainly confined to the surface 6-inch layer, its amount diminishing suddenly below. The reaction too is highly acidic, especially below the six inches depth.

Discussion

(1) Application of General Principles

In order that the soil-air should be completely renewed every hour to a depth of 20 cm., so as to maintain its fresh composition, it has been calculated that the rate of diffusion at the soil surface should be 7.0 litres per square meter per day at 15°C (60°F) (L. G. Romell, 1922; *See* Keen (5)). This value may be taken as a standard for assessing the relative efficiency of the different factors controlling soil aeration: it may therefore be termed "normal aeration". In Trinidad cacao fields where the temperature just below the soil surface fluctuates but little around 25°C (77°F), the normal aeration value would be 7.5 litres.*

Reference to Tables II and III shows that normal aeration was practically attained on two occasions early in the dry season at the River Estate site, and on three occasions at the La Reconnaissance site. Values much higher than normal were attained at these two sites later in the dry season, and values considerably lower than normal were attained at the College and the Las Hermanas sites when the soil was very dry. There appeared to be some relationship between the degree of moistness of the soil and the nearness of the respiration rate to the normal value; thus the average near-normal value for the five occasions cited was 7.25 litres (range, 6.94 to 7.93), and the average degree of saturation of the soil pore-spaces by water was 75 per cent. (range, 65 to 89 per cent.). The dependence of diffusion rate on degree of wetness would naturally be conjectured, since moisture is one of the main factors controlling the respiration of soil micro-organisms.

The problem of gaseous diffusion in the soil really concerns three gases, of which two, oxygen and carbon-dioxide, inter-diffuse through the third, nitrogen, which comprises 79 per cent. of the whole. If the nitrogen be uniformly distributed when respiration starts, it will be displaced towards the side from which the less dense of the other two gases, namely oxygen, is coming, and away from the source of the denser gas, carbon-dioxide. Thus, oxygen will pass downwards into the soil from the atmosphere faster than carbon-dioxide passes upwards, so that a gradient of carbon-dioxide concentration is set up, showing increasing values with depth. Other factors beside pore-space, such as fluctuations in temperature of the soil and of the outside air, changes in atmospheric pressure, and the prevalence of winds, also affect gaseous diffusion within the soil, but they are relatively unimportant and probably account for no more than about 10 per cent. of the total effect (5). They are particularly ineffective in tropical orchards, such as the cacao fields of Trinidad, because here their actual magnitudes are small.

According to Buckingham's findings, the rate of escape of carbon-dioxide at the soil surface is directly proportional to the gradient of carbon-dioxide concentration in the soil-profile, provided total free pore-space remains constant. For the cases cited, the average carbon-dioxide gradient was 0.080 per cent. per cm. (range 0.046 to 0.127 per cent. per cm.). This means that the soil as a whole theoretically was able, under normal

* This value is derived from the first by application of the rule that the rate of diffusion is proportional to the square of the absolute temperature (t°C+273).

moisture conditions (*i.e.* about three-quarters of saturation), to produce sufficient carbon-dioxide to maintain a concentration of the gas equal to 0.80 per cent. at 10 cm. depth, or 8.0 per cent. at 100 cm. depth (about 3⅓ feet). The larger of these two values might be regarded as dangerously high, suggesting toxic conditions for roots that may have penetrated so deeply*.

The consumption of oxygen and the production of carbon-dioxide in a soil are attributed to three main agencies, namely, (*a*) respiration of micro-organisms which bring about the decomposition of soil organic matter, (*b*) respiration of living plant-roots, and (*c*) non-enzymotic oxidation of carbonaceous residues (8). The composition of the soil-gas at any instant depends on the intensity of the processes controlled by these three agencies. The rate of respiration of soil micro-organisms is often taken as a measure of "soil fitness", because the liberation of plant nutrients (particularly nitrogen), through the decomposition of humus, is chiefly controlled by the activity of aerobic bacteria. Evidently the two sandy cacao soils in question are capable of producing, under suitable moisture conditions, sufficient carbon-dioxide to maintain a relatively high carbon-dioxide gradient. Their contents of organic matter (Table V) and their complements of micro-organisms thus appear to be adequate and their reaction not too acid† to inhibit desirable biological transformations.

Applying Buckingham's formula to the data, it will be noted (Table I) that an average carbon-dioxide gradient of 0.080 per cent. per cm., and an average diffusion rate of 7.25 litres per square metre per day (nearly the normal value), correspond to an "effective pore-space" value of nearly 24 per cent. (the range for the five cases is 18 to 30 per cent.). Hence, for the normal rate of diffusion to be maintained, the *total free air-space* of the soil should not vary much from this value. Actually, the magnitude of the average free air-space in the five cases under consideration (measured as the difference between total pore-space and space occupied by water at the times of sampling) was only 12 per cent. (range, 5 or 8 to 17 per cent.), that is, only one-half of the effective pore-space value as derived from Buckingham's formula. This discrepancy may partly be attributed to the method of calculating free air-space, whereby it is assumed that no compression of water occurs when a dry soil containing colloidal matter is wetted, a supposition which is substantially incorrect, but the error introduced in ignoring the compression effect is probably not sufficiently large to account fully for the difference in question.*

The real explanation probably lies in the fact that both "effective pore-space" and actual "free air-space" are derived values, whose assessment in each instance depends on two entirely different experimental determinations, neither of which is based on a precise or highly accurate method. Further, only relatively few examples are involved in the comparison, so that a high degree of concordance cannot be expected. Nevertheless, considering all the comparable data for estimated effective pore-space and for actual free air-space (Table IV), the ratio between the means of the two sets of values is not 2.0 but 1.37.

If the results obtained for free air-space of a soil at the time of sampling by means of the special constant-volume soil-borer are likely to show generally the same kind and degree of experimental error as those for the five cases cited, then the "normal" value indicated by the Trinidad results might be accepted as a standard measure of effective pore-space necessary for adequate aeration in cacao soils. In other words, if the apparent value for "pore-space occupied by air", based on simple measurements on the constant-volume soil-core, lies in the proximity of 12 per cent.† (equivalent to about 24 per cent. "effective pore-space", which was the "normal" value derived from gas analyses), then it may be assumed that aeration is adequate.

These considerations thus seem to warrant the following important suggestion, namely, that the aeration of soils in cacao fields in Trinidad may be gauged with sufficient reliability by means of simple measurements applied to constant-volume soil-core samples, without recourse (except as an occasional check) to the more difficult and tedious soil-gas sampling and analysis. By this means, it may thus be possible to combine the qualitative with the quantitative aspects of soil-aeration investigations.

As an instance of the application of such a procedure involving this standard of comparison, the data obtained by Dr. Vine at the River Estate site (Part I, Table IV) may be quoted. By estimating free air-space fortnightly or weekly throughout a whole wet season, Dr. Vine was able to show that aeration in the surface 6-inch layer of soil at this site was only medium-good during the greater part of the rainy season, but was definitely worse in the second 6-inch layer, and that the soil

* Some authorities accept the value 6 per cent. carbon-dioxide concentration as marking the upper limit of tolerance by living plant-roots, though direct experimental evidence in support of this contention is lacking. This critical concentration would occur at a depth of 75 cm. or 2½ feet in our "average" cacao soil profile.

† It is doubtful whether this condition applies also to the College soil whose degree of acidity is exceptionally high (pH 4.6: *See* Table V).

* Colloidally-adsorbed water (hygroscopic coefficient water), whose uptake is probably unaccompanied by a decrease in total pore-space volume, might account, *at most*, for about one-fifth of the capillary moisture content; *i.e.*, the average value for volume moisture content would be reduced from 36 to about 30 per cent., and the average value for free air-space would correspondingly be raised from 12 to 18 per cent.

† It is noteworthy that the value 10 per cent. has previously been accepted by certain authorities as the arbitrary lower limit of free air-space requisite for satisfactory soil aeration.

below the 2-foot depth was probably completely devoid of air for most of the time. Only when the degree of moistness of the soil was less than 80 per cent. of pore-space saturation was the free air-space greater than 10 per cent. of the whole volume of the soil, denoting more-or-less normal aeration.

(2) Dry Season *versus* Wet Season Conditions in Trinidad Cacao Fields

It will have been noticed that the limited amount of data for gas diffusion which Mr. Thompson was able to collect at the four cacao sites refer entirely to *dry season* conditions when the moisture content of the soil (except on one occasion) was relatively low, though seldom very low (*see* Table IV). They therefore afford no information regarding the relationship under wet conditions between carbon-dioxide concentration at various depths, soil porosity at different moisture contents and the rate of escape of carbon-dioxide at the soil surface. (The sparse gas-diffusion data collected by Dr. Vine, while they referred mostly to wet season conditions, concerned solely River Estate, and his gas analyses were confined chiefly to the surface layer). The abundant *gas analysis* data procured by Mr. Thompson, for both dry and wet seasons, have already been summarised in Table VI of Part II of this series of articles, but only mean values were given for various depths at the four sites. At the College site, soil-gas was analysed on nine occasions in the wet season of 1940, and on six occasions in the dry season of 1941. At River Estate, analyses were made six times in the wet season and seven in the dry. At La Reconnaissance, six times in the wet season and eight in the dry, and at Las Hermanas, twice in the wet season and five times in the dry. The summarised data for carbon-dioxide contents are again presented herewith in Table VI, but in addition, the *gradients* of carbon-dioxide concentration are given, and these clearly reveal the entirely different conditions of aeration that are liable to occur in the wet season as contrasted with the dry.

The data in Table VI are arbitrarily divided into values referring to dry conditions and values referring to wet conditions, as previously defined. In general, the moisture content of the soil under wet conditions occupied about 85 per cent. of the total pore-space volume, and under dry conditions about 60 per cent., the remainder, 15 and 40 per cent., being occupied by air.

(*a*) Under *dry conditions*, the carbon-dioxide gradients were steady and sufficiently constant to warrant the acceptance of their averages as characteristics of the four different cacao sites. From the mean values for gradients and diffusion rates, the effective pore-space values have been derived as before from Buckingham's table; they range from 20 to 36 per cent. (mean 26.5 per cent.), the lowest value being given by the Las Hermanas (clay) site and the highest by the La Reconnaissance site. The corresponding mean free air-space values range from 14 to 24 per cent. (average, 19 per cent.), showing a mean ratio to apparent effective pore-space of 1.39.

(*b*) Under *wet conditions*, the results obtained stand out in marked contrast to these dry season results. Thus, carbon-dioxide gradients were very irregular and, instead of being steady, tended to diminish rapidly down the profile, indicating that gaseous diffusion was greatly impaired or even prevented when the free air-space of the soil was diminished by water uptake. The values for carbon-dioxide *contents*, unlike those for gradients, were nearly constant for all depths down to 4 feet; in many instances they attained magnitudes approaching the presumed "toxic limit", notably at the River Estate site at all depths, and at the Las Hermanas (clay) site below the 18 inches depth. It is impossible to calculate effective pore-space values for the wet conditions, since no data for diffusion rate were secured, but average values for free air-space, derived from total pore-space values and soil moisture contents, are available and may be used for this purpose; they show that the soil at the three sandy sites down to the 12-inches depth seldom contained more than about 6 per cent. of free air-space, which is below the 12 per cent. limiting value tentatively accepted as marking inadequate aeration. At the College site, the mean free air-space under wet conditions reached 10 per cent. of the soil volume or 22.5 per cent. of the total pore-space. At the River Estate site, the corresponding values were 6 per cent. and 11.5 per cent., and at the La Reconnaissance site, 3 per cent. and 6.0 per cent. By contrast, the mean free air-space at the Las Hermanas site seems to have maintained a relatively high value during wet conditions, namely, about 17 per cent., or 31.0 per cent. of the total pore-space. This last result for the clay site cannot be accepted without further investigation, but it is clear from the profile data that the Las Hermanas soil is so compact below the 12 or 18-inches depth that very little air is present when the soil is wet, and carbon-dioxide concentrations may often rise to dangerously high values.

It has already been stressed that the growth and reproduction of the cacao tree in Trinidad mostly take place during the wet season, so that chief interest in soil aeration studies naturally lies in the conditions that obtain during the wet season rather than the dry. Sufficient evidence has been adduced by these preliminary investigations to demonstrate that the soils occurring at the four sites which were examined in detail display marked differences and peculiarities when their moisture status and aeration are followed through a complete yearly cycle, and there seems to be little doubt that these differences and peculiarities are closely related to the producing capacity of the soils for cacao. In particular, it has been shown that, during the wet season, the soils are frequently saturated with water for relatively long periods (especially below the

Table VI

Average Wet and Dry Season Values for Concentrations and Gradients of Carbon-dioxide in the Soil-Gas at Four Different Cacao Sites

Depths (cm.)	(A) College		(B) River Estate		(C) L.R.C. Estate.		(D) Las Hermanas Estate.	
	Carbon-dioxide concentration (Per cent.)	Carbon-dioxide gradient (Per cent. per cm.)	Carbon-dioxide concentration. (Per cent.)	Carbon-dioxide gradient (Per cent. per cm.)	Carbon-dioxide concentration. (Per cent.)	Carbon-dioxide gradient (Per cent. per cm.)	Carbon-dioxide concentration. (Per cent.)	Carbon-dioxide gradient (Per cent. per cm.)
				Dry Conditions				
10 ...	0.5	0.050	0.5	0.050	0.2	0.020	0.8	0.080
25 ...	1.1	0.044	1.6	0.064	0.8	0.032	1.7	(0.068)
45 ...	1.7	0.038	3.2	0.071	1.4	0.031	3.8	0.084
90 ...	3.4	0.038	5.2	0.058	3.4	0.038	7.6	0.084
120 ...	3.7	0.031	6.8	0.057	4.2	0.035	—	—
Means ...	—	**0.040**	—	**0.060**	—	**0.033**	—	**0.083**
	Diffusion rate	litres 3.28	Diffusion rate	litres 7.54	Diffusion rate	litres 7.06	Diffusion rate	litres 5.51
	Effective pore-space	23%	Effective pore-space	27%	Effective pore-space	36%	Effective pore-space	20%
	Mean free air-space	24%	Mean free air-space	14%	Mean free air-space	14%	Mean free air-space	23%
				Wet Conditions				
10 ...	2.8	0.280	6.5	0.650	4.2	0.420	3.6	(0.360)
25 ...	3.0	0.120	8.5	0.340	5.5	0.220	3.0	0.120
45 ...	4.2	0.093	9.7	0.215	6.3	0.140	5.3	0.118
90 ...	4.5	0.050	10.0	0.111	7.3	0.081	14.3	0.159
120 ...	5.5	0.046	9.6	0.080	3.6	0.030	17.5	0.148
							4.0	0.119
Means ...	**4.0**	—	**8.9**	—	**5.4**	—	**15.9**	**0.153**
	Mean free air-space	10%	Mean free air-space	6%	Mean free air-space	3%	Mean free air-space	17%
Sampling Periods :—								
Dry	...12th Jan.-22nd Apr.		11th Feb.-27th Mar.		13th Mar.-27th May		20th Feb.-5th Mar.	
Wet	...20th Aug.-7th Jan.		29th Oct.-28th Jan.		24th Oct.-13th Feb.		2nd Dec.-6th Feb.	

6-inches depth), so that their contents of soil-gas are not only small in amount but also relatively rich in carbon dioxide, which may reach toxic concentrations on numerous occasions.

Summary and Conclusions

(1) The importance of carbon-dioxide production in soils has long been recognised, and it was first assumed that a high concentration of the gas in soil-air implied a high rate of formation within the soil, denoting rapid respiration of micro-organisms and plant-roots or quick oxidation of organic residues. While this is generally true, it is not true under all conditions, because carbon-dioxide may accumulate in one kind of soil to a much greater extent than in another, even though the rate of production is the same in both. (2) The concentration of carbon-dioxide in the soil-air is a function, not only of the rate of production, but also of the rate of escape, and Buckingham found that this in turn is proportional to the square of the free pore-space. Hence for any particular depth of soil, if two of the three factors, carbon-dioxide concentration, free pore-space and rate of escape of carbon-dioxide at the soil surface, are known, the third may readily be calculated.

(3) This principle has been applied by the writer to the soil-gas data collected by Dr. H. Vine and Mr. H. A. Thompson at four different cacao sites in Trinidad, including a clay site.

(4) It has been found that marked fluctuations in carbon-dioxide concentration occurred at various depths, depending on the amount of water present in the soil. Addition of water to a soil progressively blocks the pores and thus reduces the effective pore-space or free air-space, so that

either soil-gas is eliminated altogether or gaseous diffusion is so retarded that toxic amounts of carbon-dioxide rapidly accumulate.

(5) Evidence is adduced to suggest that free air-space values *less than about* 12 *per cent. of the total volume of the soil* are generally associated with restricted diffusion and the development of anaerobic conditions. (Free air-space was estimated in soil-samples procured by means of a cylindrical constant-volume soil-borer by determining the amount of water and solid matter, and the true specific gravity of the dry soil.)

(6) It was thus possible to follow the fluctuations in amount of soil-air in each of the cacao soils throughout the greater part of a complete growing cycle, and it was found that, during wet periods, anaerobic conditions tended to develop, most in the clay soil and least in a pervious sandy soil.

(7) Since growth and reproduction of the cacao tree proceed mainly in the wet season, the productivity of a particular cacao site may be largely decided by the frequency and length of the periods of inadequate aeration.

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CHEMICAL NOTES

(Compiled by the College Department of Chemistry and Soil Science)

Measurement of Structural Stability and Permeability and the Influence of Soil Treatments on these Properties

Methods of determining structural stability and "probable permeability" are based on aggregate and mechanical analyses. Changes in these values are brought about by cultural and cropping practices. A rotation of maize, oats, wheat and clover caused a breakdown of aggregates in comparison with adjacent grassland. Rotations of vegetable crops over 21 years produced still poorer structural conditions. Under all conditions farmyard manure improved soil structure; lime had no significant effect. Stability of aggregates was closely related to the organic matter content. The volume weight of soil is inversely related to structural stability, probable permeability, and organic matter content. —(*Brit. Chem. Phys. Abstrs.*, B.III, 1941, p.313.)

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Phosphate Deficiency and the Sugar Cane

According to the *Report of the 61st Annual Meeting of the Hawaiian Sugar Planters' Association*, (1941), earlier experiments indicated that on a soil very deficient in available phosphate definite losses of sugar were experienced when a phosphate application was not made at the time of planting cane. It has now been shown that on a soil which showed a response to phosphate, though not nearly as deficient as the one previously used, there was no significant effect from time of application of phosphate up to four months after planting.

Another experiment gave fairly good indications that phosphate deficiency is one of the factors inducing tasseling in sugar cane. The fewest tassels were produced on cane which received superphosphate three months after planting.

* * *

Cork Substitutes

As a result of the War, imports of cork have almost, if not entirely, ceased in various parts of the world. Consequently, ingenuity has had to be exercised in providing substitutes. For obvious reasons stoppers for bottles were one of the earliest articles for which replacement was required. One of the countries affected was India, where the imports of cork from Europe very soon ceased, and the need for a substitute material for use as stoppers in different types of bottles, and as liners for bottle crowns and so forth, became keenly felt. The Forest Research Institute at Dehra Dun took up the matter, as explained in a Leaflet No. 6, Utilisation ("Note on Some Experiments on Cork Substitutes", by Dr. N. Narayanamurti, J. N. Pande and D. C. Roy (Research Institute Dehra Dun, 1941). Experiments were conducted on the production of corks made of wood, composition corks made of disintegrated tree barks and pith corks for hypodermic tabloid tubes. So far, experiments have shown the following suitable substitutes. Bottles stoppers: stoppers of *Cryptomeria japonica* wood suitably slotted and softened by chemical treatment; crown cork liners: composite cork made from *Erythrina suberosa* bark and bagasse fibre have been found suitable; corks for tabloid tubes: paraffin-impregnated sola pith is suitable. The methods of manufacture of these substitutes are described.—(*Nature*, 1942, Vol. 150, p. 230.)